JetController: High-speed Ungrounded 3-DoF Force Feedback Controllers using Air Propulsion Jets

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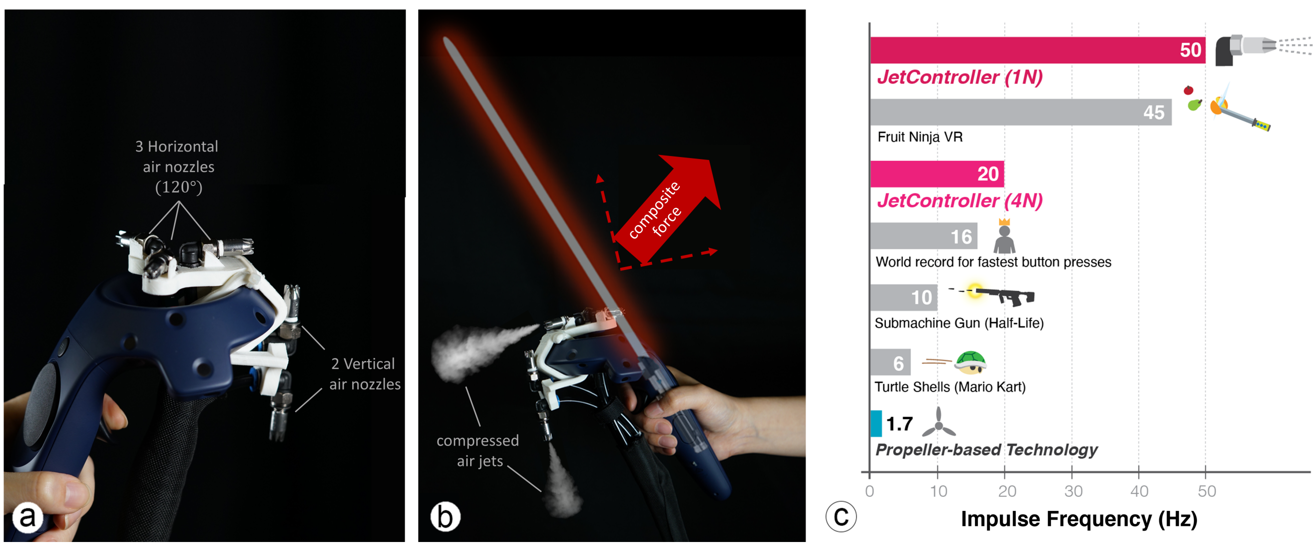

Figure 1: (a) JetController design for the HTC Vive VR controller consists of 3 horizontal and 2 vertical air nozzles, (b) provides ungrounded 3-DoF force feedback by modulating multiple compressed air jets, and (c) high-speed 3-DoF force feedback achieving impulse frequency of 20Hz at 4.0N and 50Hz at 1.0N to support popular game events. (note: the white smoke is only shown for illustrative purposes, and compressed air jets are invisible in actual use.)

ABSTRACT

JetController is a novel haptic technology capable of supporting high-speed and persistent 3-DoF ungrounded force feedback. It uses high-speed pneumatic solenoid valves to modulate compressed air to achieve 20-50Hz of full impulses at 4.0-1.0N, and combines multiple air propulsion jets to generate 3-DoF force feedback. Compared to propeller-based approaches, JetController supports 10-30 times faster impulse frequency, and its handheld device is significantly lighter and more compact. JetController supports a wide range of haptic events in games and VR experiences, from firing automatic weapons in games like Halo (15Hz) to slicing fruits in Fruit Ninja (up to 45Hz). To evaluate JetController, we integrated our prototype with two popular VR games, Half-life: Alyx and Beat Saber, to support a variety of 3D interactions. Study results showed that JetController significantly improved realism, enjoyment, and overall

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experience compared to commercial vibrating controllers, and was preferred by most participants.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

High-speed haptic feedback, air propulsion, ungrounded force feedback.

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1 INTRODUCTION

Haptic feedback enhances virtual experiences. Many types of haptic feedback are provided 1:1 to user input, such as digging in Minecraft and throwing turtle shells in Mario Kart; while some are provided many-to-one, such as slicing multiple fruits in Fruit Ninja with a single swing, and firing automatic weapons in Halo and Half-Life. The speed of human button presses ranges from about 6Hz for an average person to 16Hz for one of world's fastest players [19]. For automatic weapons, the frequency is up to 10-15Hz in games such as Halo and Half-Life. In Fruit Ninja VR, players can slice fruits in any direction, ie. 3 degrees of freedom (DoF), at up to 45Hz.

Vibration motors, such as those based on eccentric rotating mass (ERM), have long been embedded into controllers to provide haptic feedback [18]. Linear resonant actuator (LRA) provides improved precision and faster response time to provide richer vibrotactile patterns, and are used in smartphones, such as iPhone's Taptic Engine, and modern console and VR controllers, such as the Vive controllers. However, vibrotactile feedback is limited in fidelity due to limited directionality. Larger solenoid-based approaches such as Striker VR [30] provide linear impulses in 1-DoF, but it is not able to provide persistent force feedback. It also creates unintended oscillation forces in the opposite direction as its internal moving mass returns to its initial position.

3-DoF (degrees of freedom) force feedback devices have been developed to significantly improve haptic feedback fidelity. Falcon haptic controller [17] uses 3 motors to drive 3 parallel arms to provide 3D force feedback, but its grounded design and small operating space (10x10x10cm) severely constrains usability. To allow users to freely position and move controllers, researchers have recently developed ungrounded 3-DoF force feedback technologies based on propellers. Thor's Hammer [9] uses 6 orthogonal propellers to provide ungrounded 3-DoF force feedback, and is capable of generating 4.0N of forces at a weight of 692 grams. However, because propellers must physically spin up and slow down, it has a maximum impulse frequency of less than 2Hz, which is slower than many types of common haptic events.

We present JetController, a novel high-speed 3-DoF ungrounded force feedback technology capable of supporting the speed of human button presses and high-speed game events. It combines multiple compressed air jets as shown in Figure 1 to achieve composite forces in 3-DoF. By using high-speed pneumatic solenoid valves and circuitry, JetController can support full impulse frequency of 20-50Hz at 4.0-1.0N, which is more than 10 times faster than propeller-based approaches. Figure 1.c summarizes the frequency of several types of haptic events and ungrounded force feedback technologies, showing a wide range of haptic events in games and VR experiences supported by JetController.

When designing the nozzle layout, our goal was to support normal controller usage while avoiding blowing air on users. Therefore we designed the handheld device to have 3 horizontal nozzles that are 120° apart, as shown in Figure 1, plus 2 vertical nozzles. To manage noise and minimize weight, we selected miniature noise-reducing air nozzles that reduce noise by 65% [24]. The overall handheld weight, excluding the VR controller, is 158 grams with a volume of $997cm^3$, which is 77% lighter and 89% more compact compared to propeller-based devices [9].

When designing JetController's pneumatic control system, our goals were to optimize for strong force, low noise, high impulse frequency, and fast response time. However, the complex effects and tradeoffs of several key design factors of a compressed air-based propulsion system have not been established by prior literature. Therefore, we systematically evaluated 3 key design factors: 1) tubing size, 2) tubing length, and 3) use of nozzles, and their effects on 4 performance metrics: 1) force magnitude, 2) noise, 3) impulse frequency, and 4) response time. Our findings guided our design for a high force, low noise, and high-speed system, and should help future haptics developers optimize for their specific goals.

To evaluate JetController, we integrated our prototype with two highly-rated best-selling VR games, Beat Saber [29] and Half-Life: Alyx [15], to demonstrate both high-speed and persistent force feedback for a variety of 3-DoF interactions. Results from our 24-person study showed that JetController significantly improved realism, enjoyment, and overall experience ($p<0.001$ for all) compared to commercial vibrating controllers, and was preferred by 88% of the participants.

Our main contributions are as follows:

- JetController is the first high-speed 3-DoF ungrounded force feedback technology capable of supporting the speed of human button presses and automatic weapons in games and VR experiences.
- We systematically characterized the complex relationship of key design factors of a compressed air-based propulsion system, including: 1) tubing size, 2) tubing length, and 3) use of nozzles, and their effects on 1) maximum force, 2) noise, 3) impulse frequency, and 4) response time, to help haptics developers optimize their system designs.
- We open-sourced our JetController implementation at jet-controller.org[1], so that researchers can explore a system that has been shown to significantly improve realism, immersion, and enjoyment and that was preferred by participants compared to commercial vibrating controllers.

[1] Github repo: https://github.com/ntu-hci-lab/JetController

2 RELATED WORK

To place JetController in the context of related work, we focus our discussion on devices that provide externally grounded, body-grounded, ungrounded, and illusion-based force feedback, as well as air propulsion-based systems.

2.1 Externally Grounded Force Feedback

Externally grounded force feedback systems such as Phantom [13], HIRO [5], Falcon [17] and SPIDAR [16] are fixed to the environment and are capable of providing 3-DoF force feedback, in order to simulate haptic experiences such as textures, recoil, momentum, and the physical presence of objects. These devices are capable of providing strong forces with fast response time. However, the operating ranges of these grounded devices are limited to a small working area around its attachment point to the environment, thus severely restricting controller movement (e.g. pointing in different directions and motions such as slicing) and user movement (e.g. turning, walking). In comparison, JetController expands and can fully support user mobility, by either being tethered over a single air tube to a stationary air compressor, similar to how PC-based VR headsets are tethered to the PC and power source, or can be completely mobile using compressed air tanks and placing the entire system in a backpack.

2.2 Body-grounded Force Feedback

Instead of being grounded to the environment, body-grounded devices allow the operating space of the force feedback devices to move with the user. For example, hand-grounded force feedback devices can render grasping and touching feedback utilizing motor [4], or a brake to stop movement of the fingers [2, 25]. Choi *et al.* [4] proposed a handheld virtual reality controller using a servo motor to push or pull the user's hand, enables force feedback such as grasping, touching and triggering. There are also haptic gloves [3] providing force feedback with simple brake structure to stop movement of fingers, thus making the device lighter and more robust. One key limitation of body-grounded devices is that there are few locations to ground them on the body, making it challenging to generate forces in enough directions to support 1-DoF and 2-DoF force feedback and impractical for 3-DoF. In addition, for any force generated, there is a reaction force that could break the haptic illusion and negatively impact the experience.

2.3 Ungrounded Force Feedback

Researchers have explored several techniques to create ungrounded force feedback. Gyroscopic effects, in which a spinning wheel tries to conserve energy by rotating the wheel perpendicular to the spinning axis, are used to create ungrounded torque feedback on handheld haptic controllers [31, 32]. However, its force feedback is resistive force to change in orientation, rather than active force feedback in 3-DoF.

Striker VR [30], ElasticVR [28], and ElastImapct [27] move an internal mass linearly to generate impulse force feedback. ElasticVR and ElastImapct use motors to pull and release an object attached to elastic bands, similar to a slingshot, to render impact in a single direction on hands and on VR headsets. However, it requires 5 seconds for each impulse, such that its maximum impulse frequency is about 0.2Hz. Striker VR is solenoid-based and can move the internal mass much more quickly. However, there is an unintended reaction impulse force when returning the internal mass. They also cannot dynamically vary the impulse duration nor generate persistence force feedback to support different types of haptic events, such as cutting different types of fruits in Fruit Ninja.

2.4 Illusion-based Force Feedback

Several projects have explored using various types of haptic sensations to create the illusion of directional forces, weight, shape, and stiffness. Lead-Me [1] and Traxion [20] are hand-held and miniature devices that explored the non-linearity of human force perception. They both use a small mass that oscillates asymmetrically along a single axis, with a fast acceleration in the intended direction and a slower acceleration in the opposite direction. This asymmetric acceleration is perceived as a unidirectional force. However, because these do not provide true directional forces, the force direction are sometimes incorrectly recognized by users, even when applied for 2 seconds [1].

Shifty [33] is a rod-shape haptic device that can change its weight distribution to enhance the perception of weight, while Transcalibur [23] used weight shifting to render different object shapes in 2D. PaCaPa [26] is a cuboid-shaped handheld device with two wings that open and close to provide pressure on users' plams and fingers. Adjusting the pressure on user's palm and fingers dynamically enables it render size, shape, and stiffness of handheld virtual objects. These approaches do not generate ungrounded forces and require users to actively move the devices in order to perceive the feedback, as Shifty and Transcalibur provide passive haptics and Pacapa simulates handheld tools hitting virtual objects.

2.5 Air Propulsion-based Ungrounded Force Feedback

A few projects have used compressed air-based propulsion for force feedback. AirWands [21] is a pen-shaped controller with two air nozzles aligned on a single axis generating 1-DoF force feedback by releasing compressed air through nozzles. Jetto [7] integrates a smart watch with a servo controlled rotating air nozzle, and uses compressed air from a miniature air tank to provide lateral force feedback in 2-DoF. The nozzle rotates 360 degrees and each full rotation takes 2.6 seconds to complete.

AirGlove [8] uses air nozzles attached to the hand to generate persistent forces in 3-DoF to simulate objects with different weights. It uses proportional valves which can only modulate air flow at less than 5Hz. HeadBlaster [12] is a wearable motion simulator that uses headset-mounted nozzles to simulate the sensation of persistent inertial and centrifugal forces in 2-DoF. Its pneumatic control system uses mechanical relays and solenoid valves that both have a maximum operating frequency of 5Hz.

Several projects have recently explored propeller-based propulsion. Wind-Blaster [11] uses 2 wearable wrist-mounted motors and propellers to generate 1.5N of forces, and the propellers are rotated using servos. Leviopole [22] adds propellers to a handheld device to simulate the experience of hanging onto a pole and being lifted. Aero-plane [10] used 2 jet propellers mounted to a handheld controller to create the illusion of shifting weights.

Thor's Hammer [9] provides ungrounded 3-DoF force feedback using six sets of motor and propeller to generate 4.0N of forces in 3-DoF. However, as reported in its system evaluation, the propellers take a constant 300ms to spin up to generate forces between 1.0-3.0N, and takes 200ms-300ms to stop. Similarly, Aero-plane also reported 300ms of force rise time. Therefore, Thor's Hammer has a maximum impulse frequency of 2Hz at 1.0N and 1.7Hz at 3.0N. Furthermore, its slower rise time of 300ms (vs. 10-25ms for JetController) makes it more suitable for rendering gradual changes in force rather than instant impact, such as recoil forces and hitting objects.

Although some of these prior systems can achieve ungrounded 3-DoF force feedback, they maximum impulse frequencies are all lower than 5Hz, and would not be able to support even manually triggered haptic events, such as throwing turtle shells in Mario Kart. To fully support a wide range of popular haptic events, including manually and automatically triggered events, we optimized JetController for speed and use transistors to switch high-speed solenoid valves capable of 300Hz. Experimental results show that JetController can achieve full impulse rate of 50Hz at 1.0N and 20Hz at 4.0N, which is significantly faster than the world record for human input rate (16Hz) and also the rate of automatic weapons in games (10-15Hz).

3 SYSTEM DESIGN AND IMPLEMENTATION

3.1 Nozzle Layout and Controller Integration

Our design goal for JetController is to support existing VR and console controllers in a light-weight and compact form factor such that users can use the controllers normally. In this paper, we present our design for the HTC Vive VR controllers as an example, and other VR and console controllers can be supported by designing custom nozzle mounting clips.

In order to generate ungrounded forces in 3-DoF, we initially considered a nozzle layout with 6 orthogonal nozzles along the 3 axes – with 2 nozzles pointing vertically and 4 nozzles pointing horizontally. We rotated the nozzles by 45°offset to avoid having a rear nozzle pointing directly at the users. However, even with the 45-degree offset, the air jets were still often noticeable when users pointed the controllers to the sides.

We revised the design to use 3 horizontal nozzles that are 120 degrees apart with a nozzle pointing directly forward, in order to provide a wider spacing around the users, as shown in Figure 2. This design provides a good balance between freedom of controller movement and magnitude of the composition forces.

We custom designed the nozzles mounts for the HTC Vive VR controller and printed them on the Ultimaker S5 3D Printer using the Tough PLA material to create a light yet durable device. All 5 nozzles and the 3D printed mounts are shown in Figure 1.

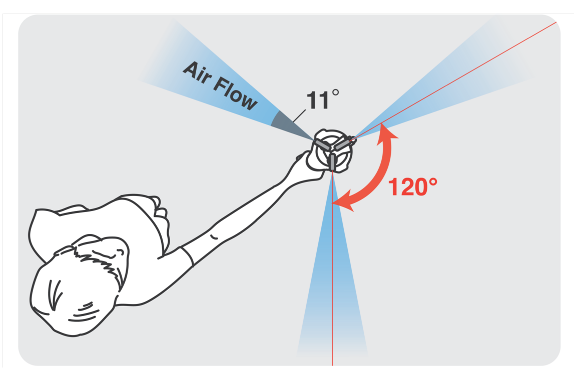

Figure 2: A schematic top view of user holding JetController. The blowing coverage of airflow follows the official spec from the manufacturer websites.

3.2 Handheld Weight and Size

The handheld portion of JetController consists of nozzles, mounting clips, and tubing. To reduce noise, we selected the miniature Silvent 1001 nozzles which are rated to reduce noise by 65%, and weigh 8 grams each with tubing connector. The 3D printed nozzle mounts have a total weight of 23 grams, and 6mm tubing weight 19 grams/meter. With 1 meter of tubing, the total weight of the handheld portion of JetController is 158 grams which is significantly lighter than propeller-based designs. As an example comparison, JetController is only 23% of Thor's Hammer's reported weight of 692 grams (without wires but with a handle).

In terms of size, we estimate using minimal bounding boxes. The nozzles and the mounting clips are 104mm x 82mm x 70mm and the five 6mm tubing wrapped together are 1000mm x 20mm x 20mm, for a total volume of $997cm^3$, which is significantly smaller than propeller-based design. As an example comparison, JetController is only 11% of Thor's Hammer's reported volume of $8999cm^3$ (without wires and without handle).

3.3 Pneumatic Control System

To enable high-speed impulses as well as persistent force feedback, we experimented with several proportional values, pressure regulators, solenoid valves, and combinations of them. We selected the Festo MHE4 high-speed solenoid valves, which are rated to have an operating frequency of 300Hz, while supporting sufficient air flow to generate more than 4.0N of propulsion force. The air pressure is controlled using high-speed versions of the SMC ITV2050 electro-pneumatic pressure regulator.

Because mechanical relays typically have a maximum operating frequency of 5Hz, we use transistors to switch power of the high-speed solenoid valves. Specifically, we used RFP30N06LE, an N-Channel MOSFET with a maximum turn-on time rated at 140ns, and a maximum turn-off time rated at 100ns.

To create composite force in any direction, 5 solenoid values are each connected to a nozzle, with 3 pressure regulators being used to adjust the air pressure for each of the 3 horizontal nozzles. Because the two vertical nozzles along Z-Axis do not actuate at the same time, we designed them to share a single regulator to reduce weight and complexity. An Arduino Nano is used to control all 4 regulators and 5 solenoid valves, as shown in Figure 3.

The compressed air could be supplied from air compressors or from high-pressure portable air tanks, such as those used for paintball. In the air compressor design, the pneumatic control system, which weighs about 3.3 kilograms, can be carried in a backpack to

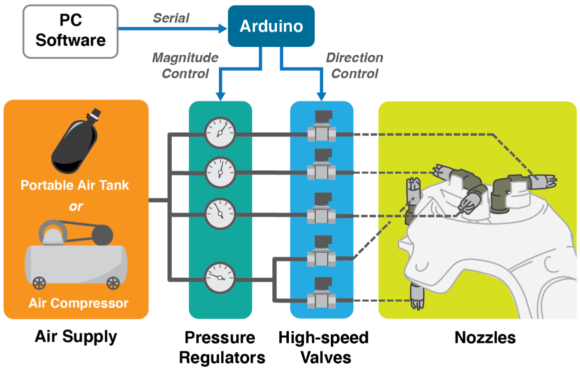

Figure 3: System architecture diagram showing 4 high-speed pressure regulators that control the force magnitude for the 5 high-speed solenoid valves to control the force direction, connected to 5 air nozzles mounted on a VR controller.

reduce the length of tubing between the solenoid valves and the nozzles for higher speed and force. This air compressor version supports room-scale VR experiences, while the mobile version can support unlimited playable area with inside-out tracking.

Figure 4 shows a fully mobile version of the system using a 1.1 liter high-pressure air tank that supports a maximum pressure of 31MPa (4500psi). The total weight of the JetController system, excluding the Vive controller and backpack, is 4.8Kg, which is similar to an HP VR Backpack PC that weighs 4.7Kg. We measured the capacity of the 1.1 liter air tank, and results showed that it could provide 570 impulses at 3.0N. Similar to CPU throttling of laptops while on battery, the force magnitude can be lowered while using the portable air tank to extend usage, to more than 2000 impulses at 1.0N.

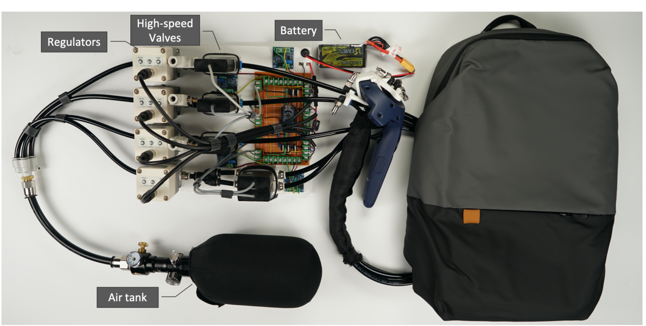

Figure 4: A mobile prototype of JetController that uses a high-pressure air tank and fits into a backpack. The dimensions of the backpack is 275x150x430mm.

3.4 Control Software and Hardware

The device control software was written in C#, and commands were transmitted to Arduino via serial port. We provided an API to convert the direction and magnitude of the resultant force into five force vectors for each nozzle. When a force vector is specified, this API first turns the vector into a local coordinate based on the orientation of controller. It then decomposes the force along the Z-axis for the upper or lower nozzles, and maps the force into the rest of three nozzles by separating the X and Y components of the vector.

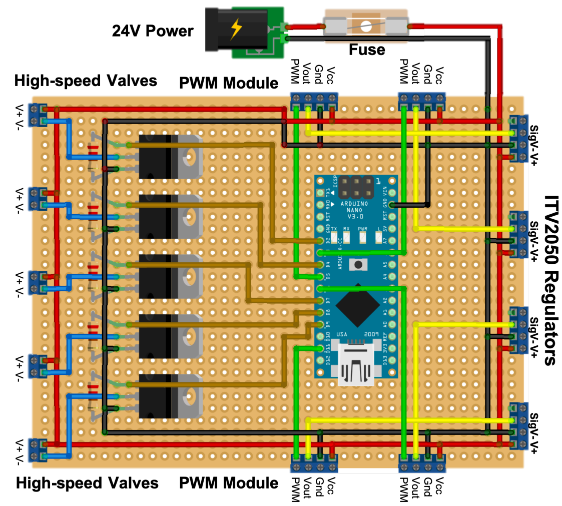

Figure 5: The circuit schematics of JetController.

To produce different force magnitudes, we control the pneumatic regulators' output pressure by using PWM-to-voltage D/A converters to produce analog control signals between 0V to 10V which correspond to output pressure of 0.005MPa to 0.8MPa. On our perfboard, shown in Figure 5, we used four 4-pin screw terminals to attach regulators' cables, four 4-pin screw terminals to attach PWM-voltage converters' wires, and five 2-pin screw terminals connected to MOSFETs for switching power to the high-speed solenoid valves.

We have open-sourced the entire system, including the 3D models of nozzle mounts, electronic schematics, Arduino code, and control software written in C# at JetController.org.

4 SYSTEM EVALUATION

To design a high-speed and lightweight controller while minimizing noise, we needed to understand how factors such as tubing size, length, and nozzles affect these design goals. However, the complex relationship between these design factors and system performance have not been established in prior literature. Therefore, we conducted several experiments to quantify the effects of: 1) tubing size, 2) tubing length, and 3) use of nozzle on 1) force magnitude, 2) noise, 3) impulse frequency, and 4) response time. Understanding these design factors and their tradeoffs will help haptics developers optimize their system designs to achieve their specific goals.

4.1 Experimental Setup and Design

To measure force magnitude, we attached one of the JetController's nozzles to an L-Shape fitting and mounted it on an IMADA ZTS-20N load cell, which can record data at 2000Hz at up to 20N and has an accuracy rating of 0.2% full scale (0.04N). To measure noise level, we placed a WS1361C decibel meter at 1 meter distance from the nozzle.

We used an air compressors designed for factory automation, and we measured its operating noise using the decibel meter placed at 1 meter distance from the air compressor. Its operating noise was 59.8dB, which is between the noise level of refrigerator hum (40dB) to normal conversation and air conditioners (60dB) according to US CDC (Centers for Disease Control and Prevention). Air compressors similar to this would be suitable for use in arcades, exhibitions, and theme parks.

We benchmarked two tubing size (diameter 6mm vs. 8mm), two tubing lengths (100cm vs. 250cm), and two nozzle designs (open pipe without nozzle vs. Silvent 1001 nozzle), for a total of 8 configurations. We chose the two tubing lengths to correspond to a mobile version of the system or a tethered version with the control system in a backpack (100cm), vs. a tethered version of the system for which the users do not carry the pneumatic control system in a backpack (250cm).

We varied the air pressure from 0.005 MPa to 0.8 MPa, which are the minimum pressure supported by the regulator and the maximum pressure supported by the high-speed valves, respectively. For each of the 8 configurations, we measured the propulsion forces and the noise level in 60 equal steps of air pressure levels and averaged the results over 5 trials for each pressure level. An air compressor is used to provide stable input pressure of at least 0.9 MPa. All experiments took place in an unoccupied office with concrete walls, and the base ambient noise level was measured to be 51 dB. To avoid the influence caused by the activation of the air compressor, we only used data recorded while the compressor was off.

For each trial, we first set the regulator to the target air pressure and then we opened the solenoid valve for 2000ms. The measured force curve was recorded and analyzed to identify three of its properties: maximum force, rise time, and fall time. To identify maximum force, we applied a low-pass filter on data points from 500ms to 2000ms, and calculated the maximum value. After the maximum force was found, we measured the rise time and fall time as the periods from the 10% to 90% and 90% to 10% of the maximum force value respectively, based on a standard approach to calculating rise time and fall time of analog impulses [14].

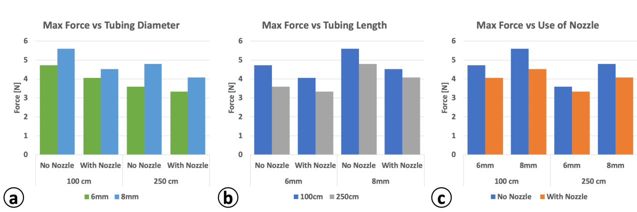

Figure 6: Maximum force under different configurations

4.2 Maximum Force Magnitude

To understand how the 3 factors: 1) tubing size, 2) tubing length, and 3) use of nozzle affect maximum force, we visualized the results using pairwise bar charts in Figure 6. Figure 6a shows that larger tubing size (diameter 8mm vs. 6mm), produced stronger forces under the same tubing length and nozzle type. Figure 6b shows that shorter tubing (100cm vs. 250cm) produced stronger forces. Figure 6c shows that open pipe produced stronger forces compared to using noise-reducing nozzles.

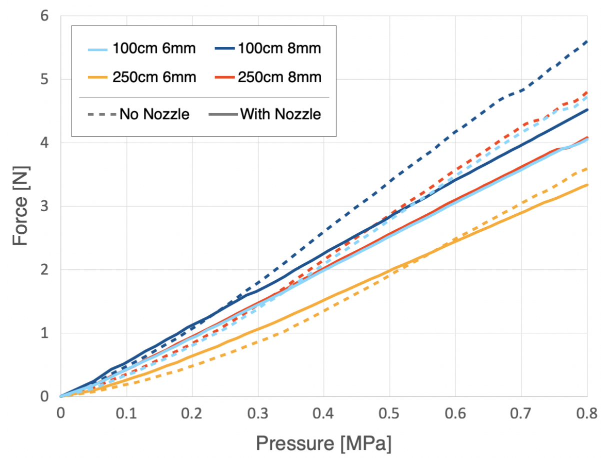

Figure 7: Maximum force vs. pressure for all 8 configurations, with dotted lines representing configurations without nozzles, and solid lines representing the configurations with nozzles.

The maximum forces vs. pressure for all 8 configurations are shown in Figure 7. Using larger and shorter tubing without nozzle (8mm x 100cm) produced the highest force output, at 5.6N at 0.8MPa. Adding noise-reducing nozzles reduced the slopes of all the force curves, with the highest force output being same 8mm tubing at 100cm at 0.8MPa, but reduced to 4.5N. Moreover, we could observe that force curves of 8mm x 250cm tubing and 6mm x 100cm tubing almost overlapped exactly, showing that the increased force output of larger tubing compensated for the reduced force output of longer tubing.

4.3 Operating Noise

Noise affects user experience and is an important design consideration. Using noise-reducing nozzles reduces noise, but it also reduces the force output compared to open pipes. While the reduction of forces can be compensated by increasing tubing size, reducing tubing length, or by increasing air pressure, it remains unclear how to best design the system to achieve a desired force magnitude with minimal noise.

Figure 8 shows the noise curves for the 8 configurations, and there are 2 clear groupings of curves, with the lower-noise curves being the configurations with nozzle, and the higher-noise curves being open pipes. This shows that for a given force magnitude, the use of nozzles significantly reduced noise level, but the choice of tubing size and length has minimal effect. As an example, while multiple configurations can produce 4.0N of forces, the configurations without nozzles produced about 90 dB of noise, while configurations with nozzles produced about 80 dB. This is a reduction of about 70% in terms of amplitude ratio, which is consistent with the 65% reduction as specified in Silvent 1001's specification.

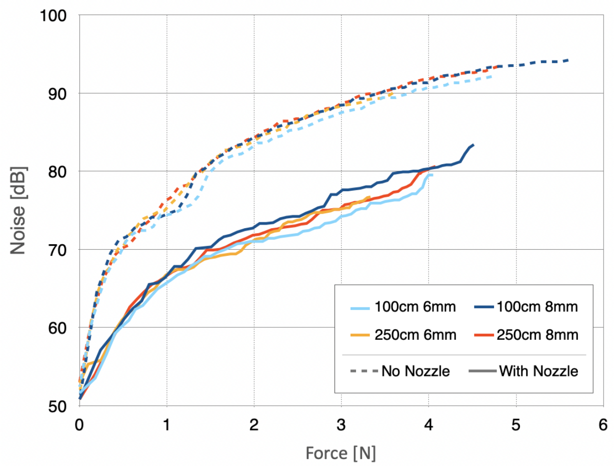

Figure 8: Measured noise level vs. force magnitude for 8 configurations.

With the nozzles, the noise level ranges from 67dB to 80dB for forces from 1.0-4.0N. According to Centers for Disease Control and Prevention (CDC), USA, 80-85dB is equivalent to "City traffic (inside the car)", 70dB is "Washing machine, dishwasher", and 60dB is "Normal conversation, air conditioner".

4.4 Impulse Frequency

Impulse frequency is affected by tubing size, tubing length, and the use of nozzles. Because nozzles have been shown to effectively reduce noise, we focus our analysis on the 4 tubing configurations with nozzles.

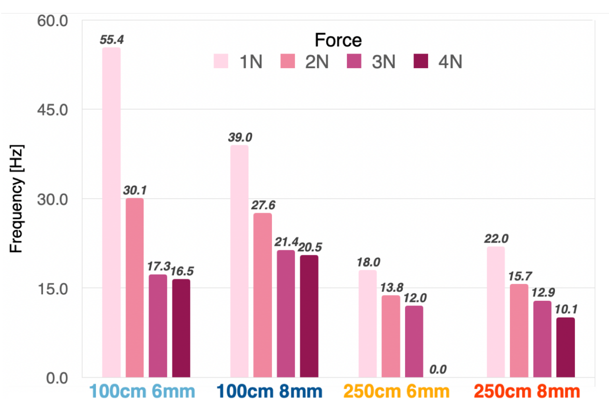

Figure 9: Maximum impulse frequency at different force magnitudes for different tubing sizes and tubing lengths, calculated based on force rise time and fall time. (The 4.0N frequency is unavailable for 6mm x 250cm tubing because it could only achieve a maximum force of 3.3N.)

Figure 9 shows the maximum impulse frequencies for 4 tubing configurations at 1N, 2N, 3N, and 4N, calculated based on rise time and fall time. For example, the combined rise and fall time for 6mm x 100cm tubing is 18ms, which is equivalent to 55.4Hz. It shows that shorter tubing consistently achieves higher frequency at the same tubing size for both 6mm and 8mm tubing, because smaller volume of air needs to be filled and released. However, the effect of tubing size on impulse frequency is more complex. Larger 8mm tubing sometimes has higher frequencies and sometimes has lower frequencies compared to smaller 6mm tubing with the same length. Overall, 6mm x 100cm tubing provides the highest frequency for 1.0N at 55.4Hz, and 8mm x 100cm tubing provides the highest frequency for 4.0N at 20.5Hz.

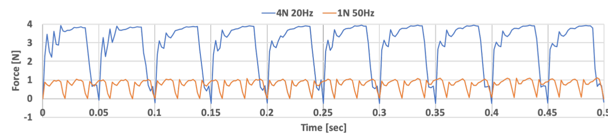

Figure 10: Actual force curve measurements of JetController, showing 50Hz of full impulses at 1.0N (6mm x 100cm tubing) and 20Hz of full impulses at 4.0N (8mm x 100cm tubing).

To demonstrate and validate that our system can indeed achieve these high-speed impulse frequencies, we programmed our system to generate 50Hz of full impulses at 1.0N and 20Hz at 4.0N, and show the load cell measurements in Figure 10. We observed that for each impulse, the force curve oscillates slightly before reaching the target force magnitude. This effect is likely due to rarefaction wave, which occurs when high-density air flows to low-density areas.

4.5 Response Time

The response time of a haptics system measures the latency between a haptics command is sent to the system and the start of force feedback. In a compressed air-based system, this latency is primarily due to the time for solenoid valves to physically open and for compressed air to flow to the nozzle. To understand how the various design factors affect response time, we recorded the timestamp when a control signal is transmitted to Arduino, and the timestamps of load cell measurements. We used 0.01N as the force threshold to determine if any force was measured, because 0.01N was the minimum measurable force magnitude of the load cell without noise.

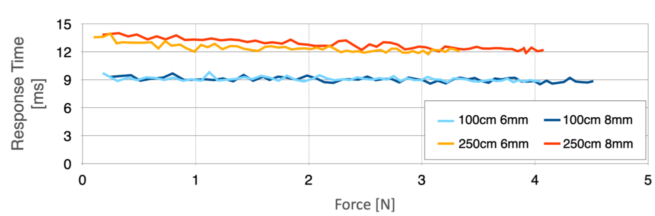

Figure 11: System response time vs. force for 4 tubing configurations using nozzles. Longer tubing length has slower response time, but tubing size and force magnitude (i.e. pressure) have minimal effect.

Figure 11 shows the response time for different tubing configurations with nozzles. Longer tubing lengths have slower response time, but tubing size and force magnitude (i.e. pressure) have minimal effect. For 100cm tubing, the response time was about 9ms, while 250cm tubing has a response time of 10-13ms.

5 USER EXPERIENCE EVALUATION

To evaluate the user experience of JetController, we designed 3-DoF haptic feedback for 2 popular commercial VR games, Beat Saber and Half-Life: Alyx. We then compared JetController (without controller vibration) to controller vibration in terms of realism, immersion, enjoyment, and preference, as well as users' ability to perceive feedback direction, frequency, and event type.

5.1 Designing Force Feedback Patterns

To design the force feedback patterns for these games, we iterated through several designs and collected feedback through 2 pilot studies.

5.1.1 Integration with Beat Saber. Beat Saber is a top-selling [29] VR rhythm game in which players swing the controllers as light-sabers to slice virtual cubes representing musical beats, as shown in Figure 12. To simulate the resistive forces from slicing the cubes in any direction at varying speed, a haptic device must be able to support persistent 3-DoF force feedback with fast rise time to simulate the initial collision.

Figure 12: Screenshots of Beat Saber: using light-sabers to slice incoming cubes.

We used the OpenVR API to read the controller's orientation and velocity in world coordinates in order to calculate the direction of resistance force, and transformed quaternions from world coordinates into local (controller) coordinates. To integrate our device with Beat Saber, we monitored the controller status using OpenVR API for vibration requests. JetController actuates when a new vibration request was received.

We conducted a pilot study with 5 users and let participants freely adjusted the force magnitude. We observed that participants gradually increased the force magnitude to make the experience more entertaining, then lowered the magnitude as the force became too strong to interfere with the timing of the playing experience. We experimented with constant and dynamic force magnitude based on swing speed. The dynamic force magnitude was a linear mapping function between controller velocity and force magnitude. However, to our surprise, participants preferred constant force of 3.0N because they felt that the same sized objects should provide the same force magnitude.

5.1.2 Integration with Half-Life: Alyx. Half-Life: Alyx is the all-time highest-rated VR game according to MetaCritic, a respected game rating aggregator [15]. It is a first-person VR shooter game, and which players use weapons to fight enemies and use "gravity gloves" to interact with objects. An example high-speed haptic feedback is when firing the automatic submachine gun, which requires a haptic device to support an impulse frequency of 10Hz.

Although Half-Life: Alyx does not have an official SDK making the game events available, we used the Source2 Engine to monitor its system logs for events relevant to haptic feedback.

We designed a total of 13 haptic feedback experiences in 3-DoF for Half-Life: Alyx, from gravity gloves to manually-operated and automatic weapons, including pistol, shotgun, and submachine gun, and various associated actions such as firing, reloading, and closing, as shown in Figure 13.

We conducted a pilot study with 5 users, and asked them for feedback as they experienced the force feedback patterns. We adjusted the force patterns according to their comments for realism, enjoyment, and comfort, then iterated through the designs. Figure 13 shows the specific force direction, timing, and ordering for each haptic feedback.

5.2 User Studies

We used a within-subject study design to evaluate the user experience of JetController without controller vibration, and compared it to a baseline of controller vibration as provided by the games. Half-Life: Alyx, in particular, is well-known for its rich design of vibrotactile patterns for various types of game events, leveraging the linear resonance actuators (LRA) in VR controllers.

To ensure all participants could perceive JetController's force feedback, we first conducted an Absolute Detection Threshold (ADT) experiment at the beginning of each session, and verified that the force magnitudes used in the games were all higher than the detection thresholds for each user.

To manage noise from affecting the haptic perception, a set of Sony WH-1000XM3 active noise-canceling headphone were used. Similar to the findings in HeadBlaster [12], these noise-canceling headphones with white noise could mask the air jet noises sufficiently that the noise from the air jets was not noticeable. All of the trials were conducted with an HTC Vive Pro HMD and a Vive controller held in participants' dominant hands.

5.3 Participants

24 Participants, 12 females and 12 male with age 21-44 ($mean = 23.6$, $SD = 4.45$), all had normal or corrected to normal vision. 33% of the participants were not familiar with VR, and 50% of the participants played games more than once per week. All but one of the participants were right-handed.

5.4 Absolute Detection Threshold (ADT)

To ensure all participants could feel all force feedback patterns we designed, we conducted a psychophysical Absolute Detection Threshold (ADT) study for 6 directions along the 3 axes. The study design is based on the study in HeadBlaster [12], and the ordering of directions was counter-balanced using balanced Latin square. The study procedure is as follows:

- The initial force is 1N, and the initial step size is 0.2N.
- For each trial, the device generates a target force for two seconds. A five-second break follows each trial.

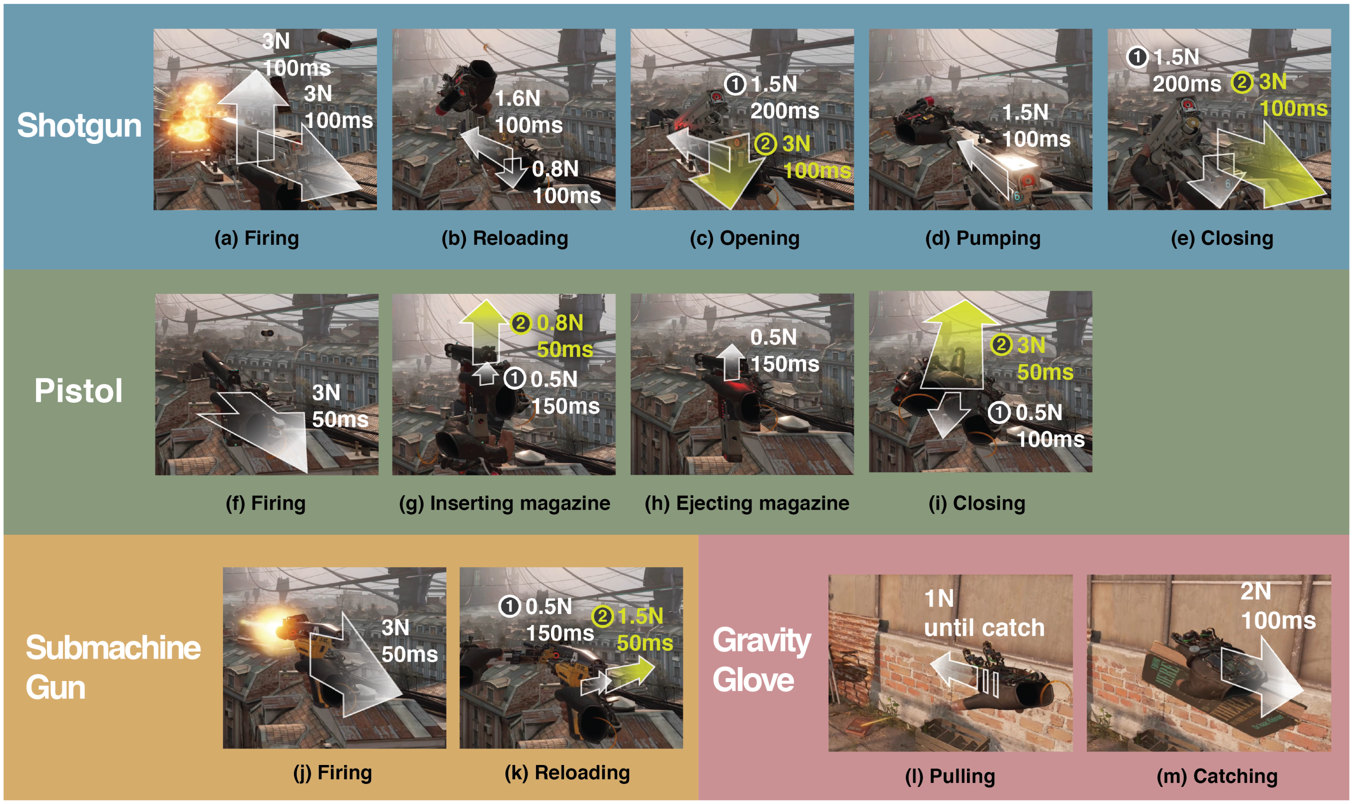

Figure 13: 3-DoF force feedback designs for haptic events in VR game, Half-Life: Alyx, with the numbering in circles representing the ordering of force sequence, and arrows representing force directions.

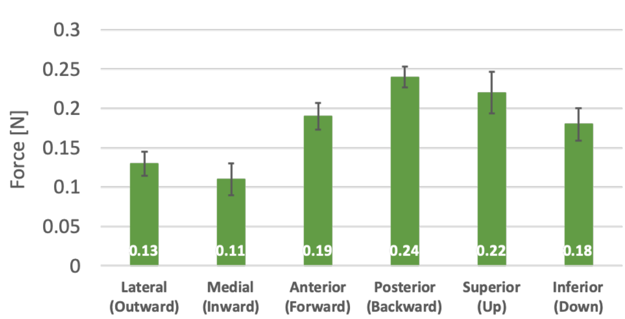

Figure 14: Absolute Detection Threshold (ADT) in 6 directions for forces provide by JetController on an HTC Vive controller.

- If the user does not feel the force feedback, the target force is increased by a step size immediately.
- If the user feels the force feedback in two consecutive trials, the target force is decreased by a step size.
- When the first reversal occurs, which means the user either feels the force after an increment or cannot feel the force after a decrement, the step size is halved to 0.1N.
- The experiment completes upon the fifth reversal. The force levels of the last four reversals are averaged.
- The experiment repeats for each of the six directions, and participants take a rest between each experiment.

All 24 participants stood comfortably in a relaxed pose and held JetController in their dominant hands. Figure 14 shows the detection thresholds for the 6 directions. The detection thresholds were lower for inward and outward compared to forward/backward and up/down.This is consistent with prior human-factor studies of wrists and forearms [6] which showed that pronation and supination have the least passive stiffness followed by flexion and extension.

The detection thresholds for all participants were lower than the minimum force magnitude used in Beat Saber and Half-Life: Alyx, which were 3.0N and 0.5N, respectively.

5.5 Application: Beat Saber

5.5.1 Experimental Procedure. The participants were instructed to stand comfortably and put on the VR headset and noise-canceling headphones, through which the game audio, verbal instructions, and background white noise were played. For each feedback condition, participants were asked to slice target cubes in 8 directions: from left to right, right to left, top to bottom, bottom to top, and diagonally. Participants were then asked to play the game freely for

2 minutes before taking a break and rating the experience, before starting the gameplay for the next haptic feedback condition. The ordering of the haptic condition was counter-balanced.

After each condition, we asked the participants to rate the realism, enjoyment, and overall experience on a 7-point Likert-scale, as well as their ability to perceive the directions of haptic feedback. After both conditions have been completed, the participants were asked to provide preference ranking and qualitative feedback.

5.5.2 Results. Figure 15 shows the average Likert-scale ratings for vibration vs. JetController without vibration. Participants reported significantly higher ratings for their ability to perceive the direction of haptic feedback (1.75 vs. 4.46), realism (3.29 vs. 4.58), enjoyment (3.71 vs. 4.92), and overall experience (3.50 vs. 4.71). Pairwise Wilcoxon signed-rank tests showed that the differences were significant for all 4 aspects at the $p < 0.001$ level.

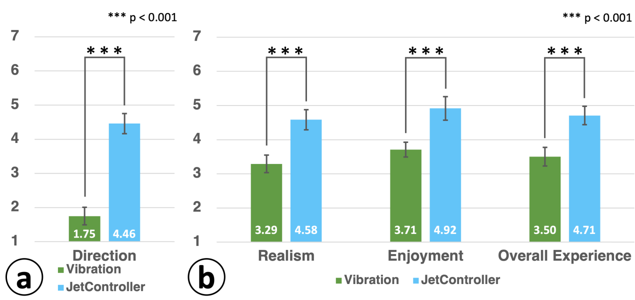

Figure 15: Average participant ratings on a 7-point Likert scale for vibration vs. JetController without vibration for Beat Saber.

In terms of preference ranking, 83.3% of participants preferred using JetController. Of the 16.7% of participants that preferred vibration, half reported that it was because the force produced by JetController was too weak, while the other half reported that the force was too strong, and that the resistive forces affected their performance while playing music tempo games.

Participants also commented that "directional force feedback is more realistic and much more fun" (P3), "directional force feedback is more perceivable than vibration in direction and magnitude" (P18), although "it is hard to judge realism because nobody has the experience of cutting cubes with light-sabers" (P11). However, P13 commented that "the resistive forces interfered with my timing when cutting." The feedback suggests that we should support customizable force magnitude to better match each player's objectives. Last, two participant reported that they "sometimes felt airflow" on their legs (P4) and body (P22), though both participants still preferred JetController.

5.6 Application: Half-Life: Alyx

Half-Life: Alyx is a much more complex game in terms of the different gestures to operate different weapons, and its many levels. As the maps are quite complex for each level, we examined all levels to identify two scenes suitable to conduct the user study. We selected an empty balcony with no enemies for the tutorial so that participants can take their time to practice interacting with weapons and the magnetic gloves. The scene for participants to play freely is a street scene in which participants have to navigate the streets while combating enemies coming from different directions, so that participants would have to turn their bodies and also point the controllers in different directions.

5.6.1 Experimental Procedure. The participants were asked to stand comfortably and wear the same noise-canceling headphones with the same audio setup as in Beat Saber. We demonstrated how to operate the 3 weapons and gravity gloves, and participants practiced using them until they are comfortable operating them before ending the tutorial and starting the gameplay.

For each haptic feedback condition, we asked participants to first use each one of the three weapons to knockdown an enemy, then use the gravity glove to fetch an object. After the participants completing these tasks, they were asked to play freely until they complete the stage. The participants were then asked to take a break and rate their experience, before starting the gameplay for the next haptic feedback condition. The ordering of the haptic conditions was counter-balanced.

After each haptic condition, we asked the participants to rate the realism, enjoyment, and overall experience on a 7-point Likert-scale, as well as their ability to perceive the direction, frequency, magnitude, and the type of different haptic events. After both conditions were completed, the participants were asked to provide preference ranking and qualitative feedback.

5.6.2 Results. Figure 16 shows the average Likert-scale ratings for vibration vs. JetController without vibration. Participants reported significantly higher ratings for their ability to distinguish the direction (2.7 vs. 4.7), frequency (3.8 vs. 5.9), magnitude (3.0 vs. 5.8), and the type (3.2 vs. 5.8) of haptic feedback. In addition, participants also rated JetController significantly higher in realism (3.0 vs. 5.3), enjoyment (4.2 vs. 6.2), and overall experience (3.8 vs. 5.9). Pairwise Wilcoxon signed-rank tests showed that the improvement for all 7 aspects were significant at the $p < 0.001$ level.

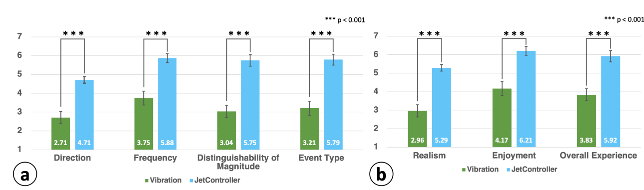

Figure 16: Average participant ratings on a 7-point Likert scale for vibration vs. JetController without vibration for Half-Life: Alyx.

In terms of preference ranking, 91.7% of participants preferred using JetController. Of the 2 participants (8.3%) that preferred vibration, one is a hardcore video game player and commented that "JetController is cool, but I'm more familiar with vibration." The other participant rarely plays video games and commented that "I felt air blowing on me while playing Half-Life: Alyx."

In terms of qualitative feedback, participants showed much excitement with JetController: "Can I buy JetController so I can play at home?" (P24) and "Wow, the force feedback is so awesome!" (P6). Participants also found the high-speed recoil forces and the sudden weight reduction from ejecting the magazines from the pistol to be especially realistic (P2, P13, P18, P23). However, one participant commented that "the force feedback of JetController is still too weak compared to real rifles because I had some shooting experience when I was in the military" (P9), and "high-frequency feedback is like vibration with stronger force" (P15), "I can sometimes feel air on my face if I aim the weapons using my wrist instead of my arm" (P3, P22).

6 DISCUSSION AND LIMITATIONS

6.1 Noise Mitigation

During development and pilot studies, we found that the air jet noises actually improved the experience for some haptics events, especially for weapons in Half-Life: Alyx. In fact, we had not used white noise during pilot studies, and all 5 pilot study participants commented that the rapid-fire noise felt realistic and made the experience much more fun. Furthermore, several of our colleagues actually preferred playing Half-Life: Alyx with regular headphones rather than noise-canceling headphones so they can hear the air jet sounds. However, while the players enjoyed the sound effects from the air jets, the noise is distracting for people nearby who are not wearing noise-canceling headphones.

In the user studies that we presented, we decided to control for the noise because we wanted users to focus only on the haptic experience. We masked the air jet noise with white noise, such that no participants reported that they heard any noise. We plan to explore how to leverage air jet sounds as sound effect, and design the overall haptic and audio experience to further improve user experience.

6.2 Expanding Controller and Posture Support

Although we have focused on VR experiences and the HTC Vive controllers as a demonstrating example in this paper, JetController can also be used for other experiences such as PC and console games. Figure 17 shows a prototype design for the Xbox One controller adapted from our VR controller design. However, we have noticed two key usage differences between console controllers and VR controllers: 1) console controllers are typically two-handed rather than one-handed, and 2) players are more likely to play in a seated posture. To address these issues, we plan to improve the design to elevate the horizontal nozzles to avoid air blowing on the hands, and also move the vertical nozzles forward to avoid air blowing on the legs.

In addition, while our current nozzle design works well for single VR controller gameplay, dual controller usage will have air blowing on users' arms. We are exploring the use of active nozzle mounts that can continuously steer the nozzles away from users' body, by sensing the position of the controllers relative to the VR headset.

Furthermore, our current nozzle design supports translational forces in 3-DoF, and we are exploring designs to additionally support rotational forces, i.e., torque, so that it can provide 6-DoF force feedback.

6.3 Mobile Weight Reduction

We had presented a mobile version of JetController as a proof-of-concept, using the same pneumatic control system as the tethered

Figure 17: JetController integrated with an Xbox One controller.

air compressor version. Although the handheld part of JetController is already compact and lightweight, the weight of the pneumatic control system (4.8Kg) can be significantly reduced by using lighter regulators and solenoid valves. Using smaller SMC ITV1050 regulators and Festo MHE3 valves, we can reduce the weight to 3.4Kg with the same performance.

Similar to how laptop CPUs are throttled while on battery, we can reduce the maximum force output which allows us to use lighter valves. For example, using the Festo MHE2 valves that supports lower air flow reduces the weight to 2.8Kg. To further reduce the weight, we can use small tanks. For example, using a 0.5 liter air tank can reduce the weight to 2.5kg. In terms of size, this lightweight version can fit inside a child-sized 8L backpack (12cm x 22cm x 25cm).

7 CONCLUSION

We have presented JetController, the first 3-DoF ungrounded force feedback device capable of supporting the speed of human button presses and even the rapid firing speed of automatic weapons. Compared to current propeller-based approaches, JetController is more than 10 times faster in impulse frequency, and the handheld portion is significantly lighter and more compact. User study results showed that compared to commercial vibrating controllers, JetController (without controller vibration) significantly improved realism, enjoyment, overall experience, and was preferred by users. Furthermore, we systematically characterized the complex relationship of key design factors of a compressed air-based propulsion system and system performance. These findings help haptics developers design systems. Last, we have open-sourced the hardware design and software of JetController, so researchers can reproduce and explore such technology.

ACKNOWLEDGMENTS

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